The <u>Hi</u>gh <u>Per</u>formance <u>Di</u>scontinuous <u>F</u>ibre (HiPerDiF) Technology:

A Sustainable Route to the Next Generation of Composite Materials

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INTRODUCTION

Highly <u>a</u>ligned <u>d</u>iscontinuous <u>f</u>ibre <u>r</u>einforced <u>c</u>omposites (ADFRCs) have the potential to offer mechanical properties, *i.e.* stiffness, strength and failure strain, comparable with those of continuous fibre composites provided that the fibre aspect ratio is high enough to allow load transfer and attain fibre failure instead of pull-out (*i.e.* fibre/matrix interface failure). Moreover, ADFRCs make it possible to overcome three of the key limitations of conventional continuous fibre composite materials:

- The lack of ductility, *i.e.* their substantially elastic-brittle behaviour, by intimately hybridising different types of fibres or exploiting pull-out mechanisms;
- The issues associated with implementing a sustainable material lifecycle, *e.g.* the integration of production and end-of-life recycled waste in a circular-economy model;
- The difficulties in producing defect-free components of complex shape with high-volume automated manufacturing processes.

The <u>Hi</u>gh <u>Per</u>formance <u>Di</u>scontinuous <u>F</u>ibre (HiPerDiF) method (Figure 1), invented at the University of Bristol (UoB), is a new way to manufacture high performance ADFRCs that is effective, sustainable, and potentially delivers the route to high throughput [1].

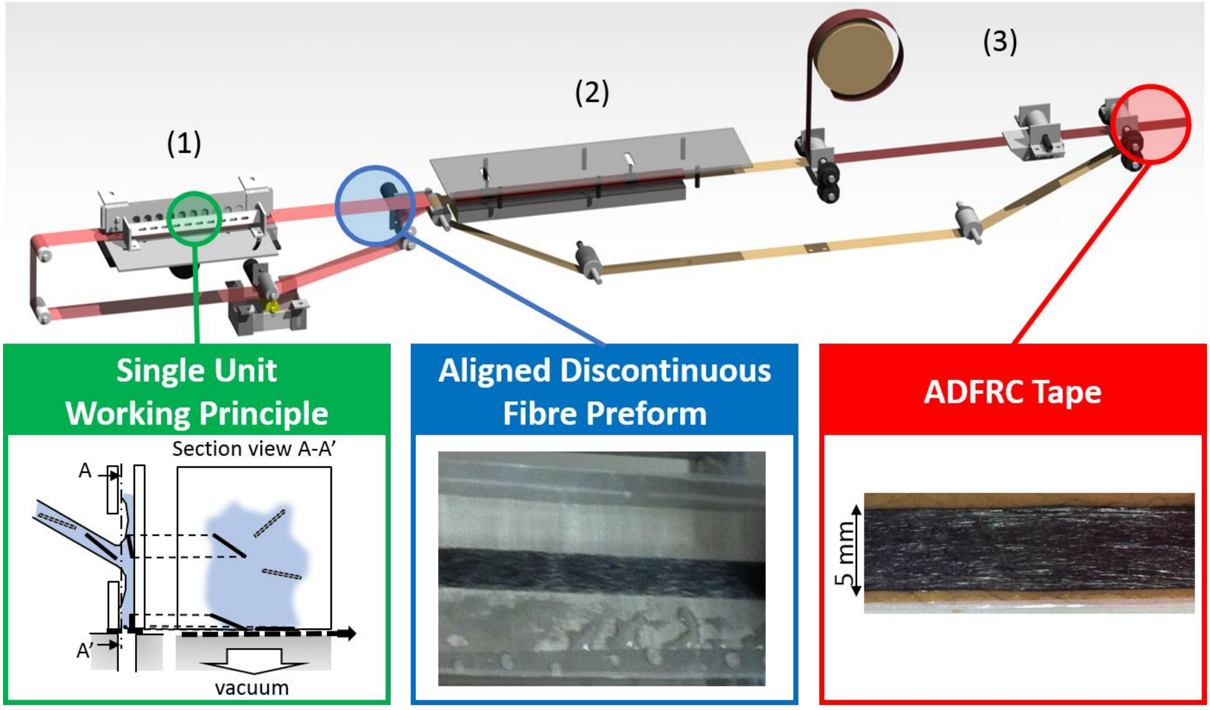

Fig. 1 The HiPerDiF method

THE HiPerDiF METHOD

The HiPerDiF method can process both synthetic fibres (*e.g.* carbon, glass, aramid and viscose) and those from natural sources (*e.g.* flax, hemp, jute) with lengths between 1 and 12 mm. The fibres are suspended in water, accelerated through a nozzle and directed in a gap between two parallel plates. The fibre alignment mechanism relies on a sudden momentum change of the fibre-water suspension at the impact with the furthermost plate. The fibres then fall on a stainless-steel conveyor mesh belt where the water is removed by suction, (1) in Figure 1. The aligned fibre preform is dried with infrared radiation to allow the matrix impregnation process, (2) in Figure 1. The dry aligned fibres preform can be finally coupled, through a suitable process, with a thermoplastic or thermosetting matrix, (3) in Figure 1.

A first machine prototype [2] produced specimens with 67% of fibres within a ±3° range from perfect alignment. By processing 3 mm high strength carbon fibres (Table 1) it was possible to achieve, under tensile load, a stiffness of 115 GPa, a strength of 1510 MPa, and a failure strain of 1.41%.

Table 1: Fibre Properties

		High Strength Carbon Fibres (HSCF)	High Modulus Carbon Fibres (HMCF)	E-Glass Fibres (EGF)	Reclaimed Carbon Fibres (rCF)
Length	[mm]	3	3	3	3
Diameter	[μm]	7	10	7	6.5
Stiffness	[GPa]	225	860	73	230
Strength	[MPa]	4344	3430	2400	1110
Failure Strain	[%]	1.93	0.398	3.29	0.5

DUCTILE COMPOSITES

The HiPerDiF method was invented within the High Performance Ductile Composite Technologies (HiPerDuCT) programme grant, a collaboration between the Bristol Composites Institute (ACCIS) and The Composites Centre at Imperial College London, aimed at designing, manufacturing and evaluating high performance composite systems with ductile or pseudo-ductile responses [3]. Pseudo-ductile behaviour was achieved with ADFRCs both by exploiting the fibre pull-out mechanism and by intimately hybridising different types of fibres in composites.

By generating intermingled High Modulus Carbon Fibre / E-glass Fibres (HMCF/EGF) hybrid composites it was possible to achieve the pseudo-ductile behaviour shown in Figure 2 [4]. The micrograph shows the level of intermingling that can be achieved with the HiPerDiF method. Three distinct segments can be identified in the stress-strain curve of Figure 2: a first linear-elastic response region (1), a plateau caused by the progressive fragmentation of the HMCF (2), and a final region dominated by the EGF response (3).

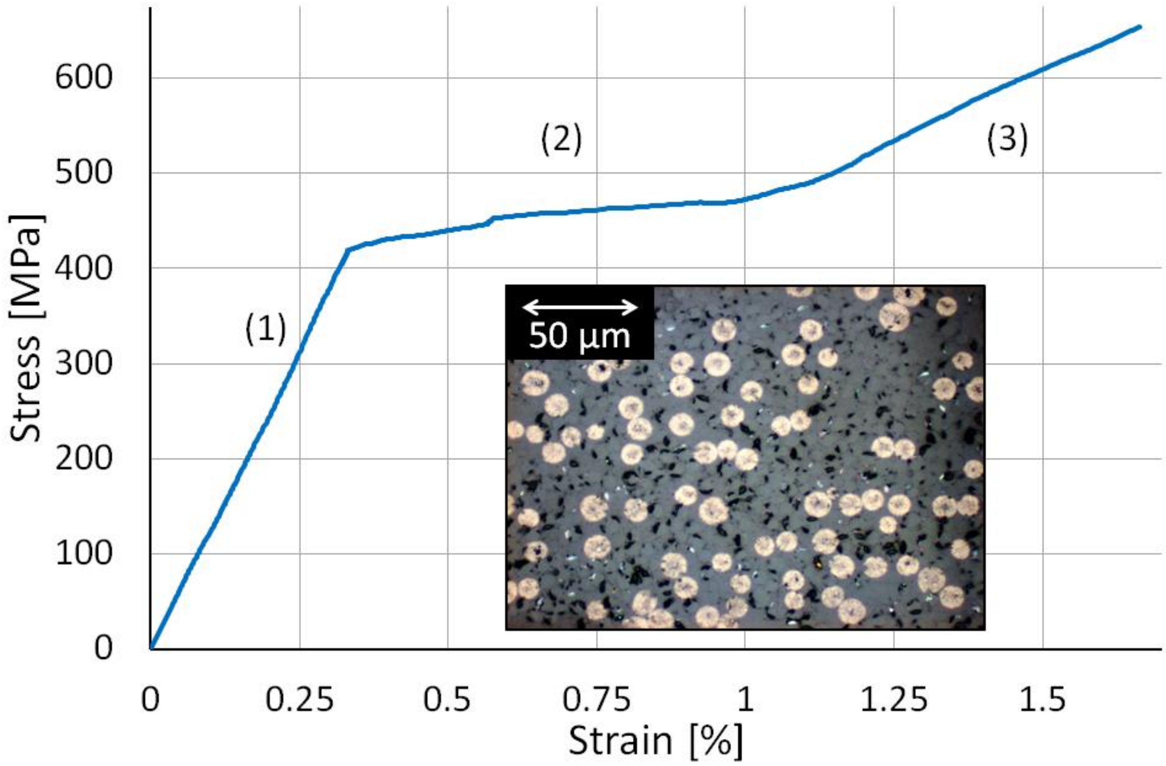

Fig. 2 Pseudo-ductile behaviour of 33% HMC / 64% EG intermingled hybrid ADFRCs [4]

SUSTAINABLE COMPOSITES

Composite materials are generally recycled in a two-step process: a fibre reclamation stage, where the fibres are retrieved by degrading the matrix, and a remanufacturing stage to produce a reusable material. Reclamation techniques can be categorised in two groups: the thermal processes, *e.g.* pyrolysis, fluidised bed pyrolysis and microwave-assisted pyrolysis, and the chemical processes, *e.g.* solvolysis and critical fluid solvolysis. In general, waste material size-reduction before, fibre breakage during and fibres chopping after reclamation lead to reclaimed fibres fragmented into short lengths. The HiPerDiF method is therefore an ideal solution to remanufacture reclaimed fibres into an economically valuable material with high mechanical properties that has a natural place in a circular economy model for composite materials (Figure 3).

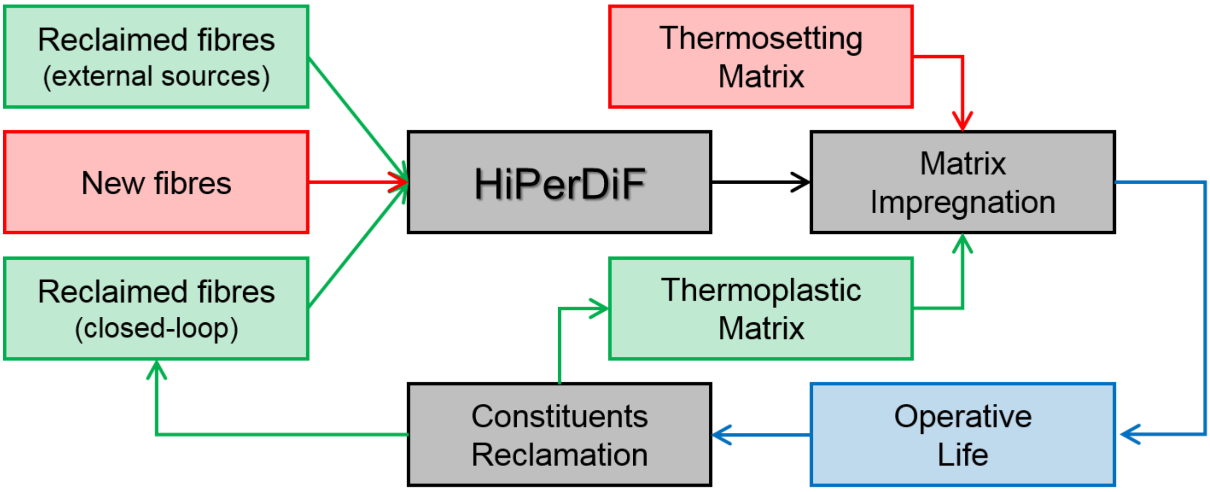

Fig. 3 The HiPerDiF method for a composite material circular economy model

The HiPerDiF method was used to remanufacture 3 mm reclaimed carbon fibres (rCF), Table 1, into a recycled ADFRC material with a stiffness amongst the highest reported in the available literature, *i.e.* 72 GPa, with a fibre volume fraction of 37% [5]. The relatively low failure properties, *i.e.* strength 600 MPa and failure strain 0.83%, arise partially from the relatively low fibre volume fraction and, to a greater extent, from the fibre degradation during reclamation; further developments in those processes will allow the delivery of recycled composites with properties comparable with the virgin material. Moreover, the possibility of the ADFRCs produced with the HiPerDiF method maintaining high stiffness over several recycling loops has already been demonstrated (Figure 4) [6]. Beside the expected reduction in failure strain, the loss of stiffness in the second recycling loop is due to fibre length reduction caused by the harsh, and unoptimised, reclamation process.

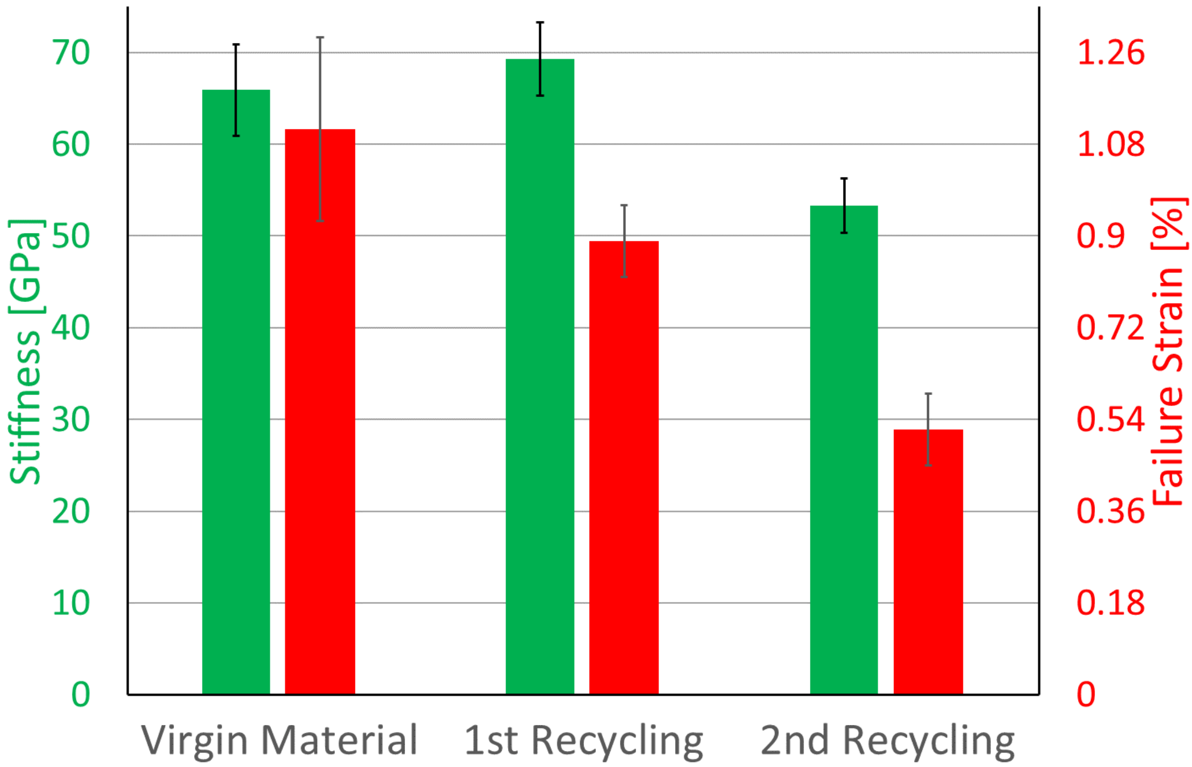

Fig. 4 Stiffness and failure strain of virgin and recycled ADFRCs.

A thermoplastic matrix, fully-recyclable high-performance ADFRC material, and the relative closed loop recycling process are currently under development at the UoB. Furthermore, natural and reclaimed carbon hybrid composites for specific applications, *e.g.* flax fibres for vibration damping, have been successfully manufactured with the HiPerDiF method.

FEEDSTOCK FOR HIGH-VOLUME DEFECT-FREE MANUFACTURING

An analysis of the defect generation mechanisms through the composites design and manufacture cycle reveals that a large proportion of these are essentially driven by the fact that the fibres are continuous, particularly when producing complex surfaces and shapes and using automated processes, *e.g.* Automated Tape Laying (ATL) and Automated Fibre Placement (AFP). ADFRCs also display "ductile behaviour" in their uncured state, this allows the productivity of current automated manufacturing processes to be significantly increased and simple stamp or vacuum forming to be used even for complex geometries, while significantly reducing a range of manufacturing induced defects. When continuous fibre tapes are deposited along a curved pathway in ATL and AFP, the fibres on the outer path are stretched while the ones on the inside are bent and kink out of plane, this generates wrinkling defects;

discontinuous fibres can rotate and slide relative to one another, eliminating these sorts of defects. When manufacturing ply-drop regions, uncured ADFRCs tapes can be stretched generating a feathered and tapered tape-end, this eliminates resin rich pockets and consequently the stress concentrations. In the case of stamp or vacuum forming of complex three-dimensional geometries, the ductility of the uncured material allows avoiding fibre bridging and tool-ply interaction generated defects. An aligned discontinuous fibre reinforced filament for 3D printing applications is currently under development at the UoB to exploit the high performance of ADFRC and the manufacturing flexibility of rapid prototyping for highly tailored applications.

CONCLUSION AND FUTURE WORKS

The HiPerDiF method can produce ADFRC material with mechanical performance comparable with that of continuous fibre composites. Moreover, it offers the possibility to manufacture highly intermingled hybrid materials with ductile behaviour or functionalised for specific applications. Furthermore, the HiPerDiF method allows to remanufacture reclaimed carbon fibres into high value, recycled materials offering a viable solution to the development of a sustainable composite material lifecycle. Finally, the adoption of ADFRC will allow to overcome many of the manufacturing induced defects and consequently increase the production rate of automated processes. This potentiality has been recognised also by the UK Engineering and Physical Sciences Research Council (EPSRC) that has recently funded a 3-year, HiPerDuCT follow-up programme, with extensive industrial support, aimed at scaling up the HiPerDiF process and at a deeper investigation of ADFRC’s manufacturing benefits and properties (Figure 5).

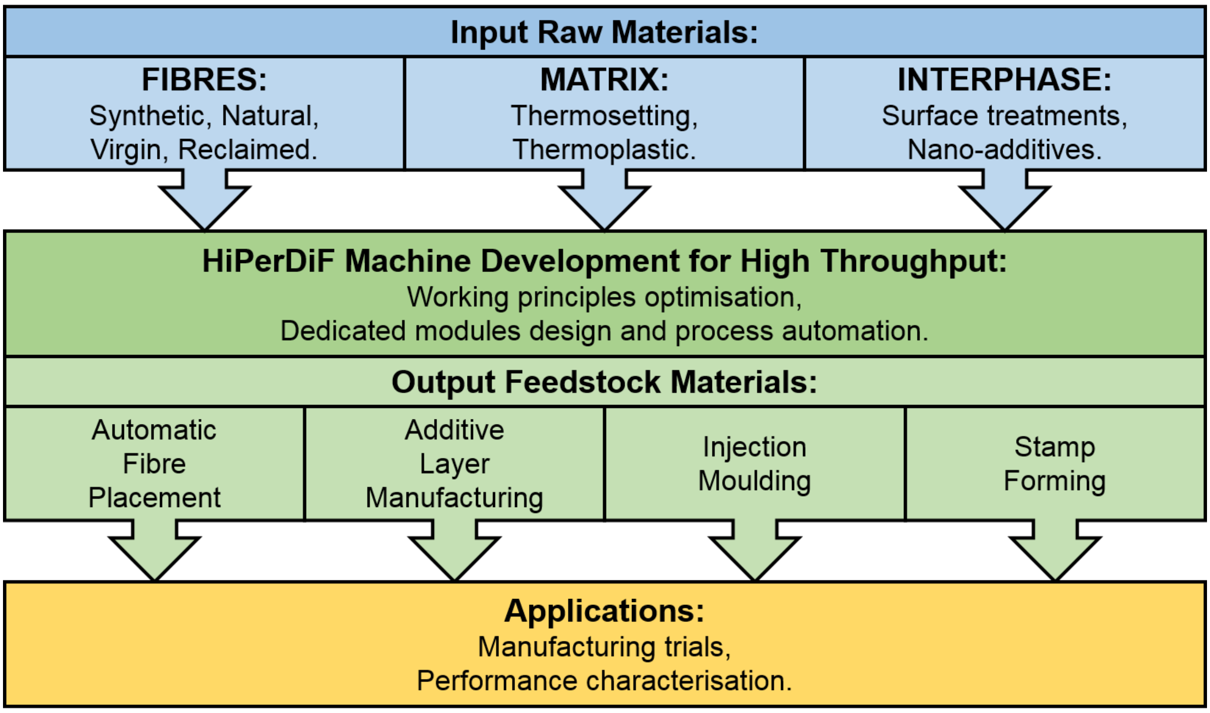

Fig. 5: "HiPerDiF: A Sustainable Route to the Next Generation of Composites"

The "High Performance Discontinuous Fibre Composites: A Sustainable Route to the Next Generation of Composites" £1.3M programme will involve four academics, four researchers and ten industrial partners, drawn from the entire value chain: from raw materials suppliers, through manufacturing processes and machine developers to end-users. The research team is, however, always interested in setting-up further collaborations and defining new project both on an academic and an industrial point of view and invites the readers to get in contact.

AKNOWLEDGMENT

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